Orthotic design and foot impression procedures to control foot alignment

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Abstract

The traditional theory on subtalar joint neutral position and intrinsic foot deformities for the evaluation and treatment of foot and ankle disorders has been the basis for foot orthotics for many years. Although clinical evaluations have suggested a relationship between subtalar pronation and a variety of lower limb problems, such as shin splints and anterior knee pain, recent research has raised serious concerns about the reliability and validity of the assessment and intervention methods. Results of recent studies in foot biomechanics suggest that the orthosis design to control foot alignment should stabilise the medial apical bony structure of the arch to control the first ray mobility and transmit load through the lateral support structures of the foot, locking the calcaneocuboid joint and decreasing strain in the plantar aponeurosis. The concept of “posting” according to a measured foot deformity is de-emphasised.

Reliable foot impression procedures are required to provide appropriate orthotic design and thus management. A prone lying position manipulated foot impression method using polycaprolactone based low temperature thermoplastic material was introduced. Ten (10) subjects were recruited to participate in the reliability tests, which were conducted by 2 orthotists specialized in foot orthotics. Results showed high intrarater and interrater reliability of the measured forefoot width and the navicular height. The reliability of the forefoot-rearfoot relationship was demonstrated by the small variance of the root mean square calculation. Subsequently orthotic intervention can be done in a more consistent manner.

Introduction

The triplanar axis of the subtalar joint forms an angle with all three cardinal planes (Manter, 1941). The triplanar motions occurring at the subtalar joint are called pronation and supination. Since pronation and supination cannot be measured directly, they are reflected by the measurement of eversion and inversion which occur along the longitudinal axis of the foot. Wright et al. (1964) investigated the action of the ankle-foot complex during the stance phase of walking in 2 normal subjects. They designed an exoskeletal goniometer system incorporating 2 sets of potentiometers along the mechanical axis of the subtalar and ankle joints. The system was used to measure and define the neutral position of the subtalar and ankle joints “when the subject was standing relaxed with the knees fully extended, the arms at the sides, feet 6 inches apart, and with a comfortable amount of toeing-out (relaxed standing foot posture - RSF)”. The results indicated that the subjects reached the neutral position of the subtalar joint at approximately 70% and 65% of their respective stance phase. Root et al. (1971) used the normative subtalar joint motion data to build on their theory of normal foot motion. They
defined the subtalar joint neutral position (SJNP), which is different to the Relaxed Standing Foot Position (RSFP) defined by Wright et al. (1964), as neither pronated nor supinated by palpation of the head of the talus relative to the navicular. McPoil and Cornwall (1994) redefined the “neutral” position of the subtalar joint during a walking cycle as the RSFP, which had an average value of 3.64° in eversion, rather than the SJNP. The average time to maximum pronation was 37.9% gait cycle and was much later than reported by both Root et al. (1971) and Wright et al. (1964). The mean path of subtalar joint motion during the first 60% of the walking cycle occurred between the static angles measured at RSFP and single leg standing (McPoil and Cornwall, 1996). The SJNP should not be the aim of orthotic intervention as the neutral position of the subtalar joint occurred at the 66% and 74% gait cycle and was supinated (Pierrynowski and Smith, 1996).

After heel strike, the calcaneus was in slight plantarflexion and this was followed by slight dorsiflexion throughout the mid-stance. It then plantarflexed again during the last propulsive period (Leardini et al., 1999). The magnitude of the midtarsal joint movement was greater than that of the subtalar joint (Huson, 1991). The first ray was slightly plantarflexed and evverted during the loading response. From heel off to toe off it dorsiflexed until 70% stance time and then began to plantarflex. It reached a plantarflexed position after 88% stance time. (Cornwall and McPoil, 2002)

There were conflicting results in the reliability of clinical evaluation methods (Elveru et al., 1988; Lattanza et al., 1988; Somers et al., 1997 and Jonson and Gross, 1997). Both the palpation method and the mathematical method of determining subtalar neutral position could not achieve a high level of interrater reliability (Smith-Oricchio and Harris, 1990). Measurement on range of inversion and eversion were unreliable (Ball and Johnson, 1993, 1996; Pearce and Buckley, 1999).

An orthosis made from a weight-bearing position cast tended to dorsiflex the first ray and invert the forefoot at the midtarsal joint. This prevented the first ray plantarflexion and inhibited first metatarsophalangeal dorsiflexion to establish the windlass mechanism (Roukis et al., 1996). Over-the-counter orthoses did not offer clinically significant improvement in foot alignment. Evaluation of custom moulded orthosis was suggested (Kitaoka et al., 1997; 2002).

A non-posted orthosis reduced maximum pronation as a posted orthosis did (Johanson et al., 1994). This de-emphasized the concept of “posting” according to a measured intrinsic foot deformity. The total contact foot orthosis is an effective device to control pronation (Mueller, 1994). The medial surface contour of the orthosis must stabilize the medial apical bony structure of the arch (Kogler et al., 1996). The orthosis should also transmit load through the lateral support structures of the foot, locking the calcaneocuboid joint and decreasing strain in the plantar aponeurosis (Kogler et al., 1999).

Objective
A foot orthosis is a mechanical device applying force through soft tissue to the bony structure to control the foot alignment. Correct fitting of the orthosis has to be done before evaluation of orthotic treatment. An appropriate foot impression method should allow minimal subjective plaster model rectification procedures (Henderson and Campbell, 1967; Colson and Berglund, 1977; Leung et al., 1998) and allow a more consistently designed orthosis. The objective of this study is to introduce a reliable foot impression method and determine the reliability by the results of the intratester and intertester reliability tests.

Materials and methods
Subjects selection criteria
Two experienced orthotists specialized in foot orthotics conducted the foot impression experiments. They were given enough time to become familiar and confident with the proposed foot impression procedures before experiments would be carried out. Ten (10) subjects, 6 to 11 years of age, were recruited to participate in the experiments for reliability tests. They were free from static foot deformities and without lower limb injuries and pain at the time of study. Informed consent was obtained from all participating subjects.

Foot impression procedures
In this study, the orthotic design was based on the University of California Biomechanics Laboratory insert approach (Campbell and

Fig. 1. The calcaneal line. (Inman, 1974). A polycaprolactone based low temperature thermoplastic material, Orfit (Orfit Industries, Wijneyem, Belgium), was used. The perforated material was 1.6mm thick. It becomes soft and transparent at 65°C and decomposed to carbon dioxide, carbon monoxide and nitrogen oxide at 280°C. The material was selected because of its elastic and self-bonding properties. Utilizing the elastic properties of the plastic material, the soft tissue of the foot was better controlled during the casting procedures. The plastic material did not slip on the hand as the plaster bandage did. Excessive force, which can result in a distorted foot shape, was not required to control the foot alignment. The need for rectification of the plaster model was thus minimal. The prone casting position was selected and the procedures adopted were as follows:

1. The subject was lying prone on the bed with the knee axis of the limb involved parallel to the edge of the examination table.

2. An adhesive tape was put on the posterior surface of the heel area along the axis of the lower leg;

3. A line perpendicular to the base of the calcaneus (calcaneal line) was drawn on the tape (Fig. 1). The navicular tuberosity was marked;

4. A piece of Orfit™ sheet (length of sheet: about 120% foot length; width of sheet: about 140% foot width at metatarsals level) was heated to 65°C in a heating water bath and brought to align with the plantar surface of the foot (Fig. 2);

5. The upper edge of the plastic sheet was bonded together (Fig. 3);

6. Both sides of the material were stretched forward and bonded together (two points only) on the dorsal surface of the foot at the instep and just proximal to the metatarsals level (Fig. 4);
Ortotic design and foot impression procedures

Fig. 5. Keeping the ankle in 90° and controlling the inversion or eversion.

(7) The foot was then adducted and dorsiflexed by force acting through the thumb on the distal portion of the fourth and fifth metatarsal heads. To control the position, the knee was flexed and the calcaneus was kept at a position with no inversion or eversion. (Fig. 5). The ankle joint was kept at 90°;

(8) Pressure was applied to the plantar surface of the lateral column of the foot so that the first and fifth metatarsals were on the same level (Fig. 6);

(9) The calcaneal line, which could be seen through the semi-transparent material on the outer surface of the plastic splint, was duplicated before the material returned to its original colour. The plastic splint was then removed by breaking the two dorsal self-bonding points (Fig. 7).

Positive model rectification
The plastic splint was filled with plaster of Paris. When the plaster inside the negative impression solidified the markings of the navicular tuberosity and the calcaneal line were transferred to the cast. The plastic splint was then removed to get the positive cast. The only rectification procedure required was the addition of plaster material to prominent navicular to relieve pressure if necessary. The medial trim line (Fig. 8) was kept with the highest point just above the navicular tuberosity while the lateral trim line (Fig. 9) was allowed to be considerably below the upper border of the fifth metatarsal shaft. The height of the heel cup was up to the level of the most posterior point of the heel to control the rolling of the calcaneus. The distal trim line projected under the plantar surfaces of the foot and ended at the proximal edge of the metatarsal heads. The positive cast was then polished with sand screen wire and dried in an oven. A 3 mm thick polypropylene sheet was then heated up to about 180°C for vacuum press forming of the orthosis.

Parameters and methods of measurement
The following parameters were measured

Fig. 7. The plastic splint after removal.

Fig. 6. Keeping the first and fifth metatarsals to the same level.

Fig. 8. The medial trim line.
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Fig. 9. The lateral trim line.

for comparison. The width of the plaster model across the first and fifth metatarsal heads was measured by a Digital Foot Measuring Device (Fig. 10) designed by the Jockey Club Rehabilitation Engineering Centre at The Hong Kong Polytechnic University (Cheng et al., 1997). The navicular height was measured by a Digital Height Gauge modified from an electronic caliper (Fig. 11). The orientation of the calcaneal line was measured by a Laser Line Apparatus (Otto Bock Orthopaedics, Germany). Both pieces of digital apparatus have an intrinsic error of less than +/-0.01 cm. The scale of the Laser Line Apparatus (Fig. 12) was modified and magnified to provide an intrinsic error of less than +/-0.5°.

Statistical analysis

To determine the intratester and intertester reliability of the foot impression method, type (3, 1) intraclass and type (2, 1) interclass correlation coefficients (ICCs) were determined for the measurement of the forefoot width and the navicular height. The aim was to have a plaster model with the calcaneal line in a vertical position. The reliability of utilizing a calcaneal line to reflect the forefoot-rearfoot relationship was determined by the result of the root mean square calculation. Measurements of the two models for each of the subjects prepared by the first orthotist were compared to determine the intratester reliability. Measurements of the first foot impression prepared by the first orthotist and that from the second orthotist were also compared to determine the intertester reliability.

Results

The forefoot width, the navicular height and the orientation of the calcaneal line of the 10 subjects were measured by the 2 orthotists. The results are shown in Table 1 to Table 3 and Figures 13 and 14.

In the forefoot width measurements, the ICC (3, 1) intratester reliability for the first orthotist was 0.95 (95% CI 0.82-0.99). The ICC (2, 1) intertester reliability between orthotist 1 and 2 was 0.95 (95% CI 0.82 - 0.99). In the navicular height measurements, the ICC (3, 1) intratester

Fig. 10. The digital foot measuring device.
reliability for the first orthotist was 0.83 (95% CI 0.46-0.96). The ICC (2, 1) for intertester reliability was 0.83 (95% CI 0.48 - 0.95).

For the orientation of the calcaneal lines, results of a paired t-test showed no significant difference (P=0.2585) between the first and second measurements of orthotist 1. Neither was any significant difference (P=0.8200) found between the measurements from orthotist 1 and orthotist 2. The root-mean-square value of the orientation of the vertical calcaneal line of the first 10 casts and the second 10 casts taken by orthotist 1 and the 10 casts taken by orthotist 2 were: 0.9618, 0.9618 and 0.9747 respectively.

Discussion

McPoil et al. (1989) compared the forefoot-to-rearfoot angles obtained from the supine non-weight-bearing, prone non-weight-bearing and sitting semi-weight-bearing casting methods. The results indicated that the same forefoot-to-rearfoot alignment could be obtained using non-weight-bearing methods but not the semi-weight-bearing method. However, only intraclass reliability was reported. Payne et al. (2001) developed a weight-bearing neutral position casting device, the Foot Alignment System. The group reported that the result has less variability and more repeatability than the traditional non-weight-bearing casting method. However, the operation of the FAS was not clearly demonstrated. Laughton et al. (2002) compared the non-weight-bearing plaster casting, partial-weight-bearing foam impression, and partial-weight-bearing and computer aided non-weight-bearing laser scanning methods of obtaining the geometry of the foot. They reported big variations in the measured forefoot width, and arch height.

In this study the Orfit™ material, which required heating to 65°C to conform to the shape of the foot, was heated in a hot water bath to the required temperature. The self-bonding and elastic properties of the material were utilised to form and control the geometry of the soft tissue.

Table 1. Forefoot width measurements (in mm) of 10 subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Orthotist 1a</th>
<th>Orthotist 1b</th>
<th>Orthotist 2</th>
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</thead>
<tbody>
<tr>
<td>Cast 1</td>
<td>65.4</td>
<td>66.7</td>
<td>63.7</td>
</tr>
<tr>
<td>Cast 2</td>
<td>64.3</td>
<td>66.8</td>
<td>62.1</td>
</tr>
<tr>
<td>Cast 3</td>
<td>68.4</td>
<td>66.0</td>
<td>70.4</td>
</tr>
<tr>
<td>Cast 4</td>
<td>69.3</td>
<td>66.4</td>
<td>67.3</td>
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<tr>
<td>Cast 5</td>
<td>74.2</td>
<td>74.9</td>
<td>76.3</td>
</tr>
<tr>
<td>Cast 6</td>
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<td>73.5</td>
<td>72.4</td>
</tr>
<tr>
<td>Cast 7</td>
<td>65.1</td>
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</tr>
<tr>
<td>Cast 8</td>
<td>70.2</td>
<td>69.6</td>
<td>72.6</td>
</tr>
<tr>
<td>Cast 9</td>
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<td>80.4</td>
<td>85.5</td>
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<tr>
<td>Cast 10</td>
<td>84.2</td>
<td>81.5</td>
<td>86.3</td>
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Table 2. Navicular height measurements (in mm) of 10 subjects

<table>
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<th>Orthotist 1</th>
<th>Orthotist 2</th>
</tr>
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<tr>
<td>Cast 8</td>
<td>39.94</td>
<td>38.04</td>
<td>41.20</td>
</tr>
<tr>
<td>Cast 9</td>
<td>43.17</td>
<td>44.53</td>
<td>45.03</td>
</tr>
<tr>
<td>Cast 10</td>
<td>44.54</td>
<td>43.17</td>
<td>43.26</td>
</tr>
</tbody>
</table>
Fig. 13. Forefoot width measurements of 10 subjects.

Fig. 14. Navicular height measurements of 10 subjects.

Fig. 15. Orientation of calcaneal line.
Table 3. Orientation of the vertical calcaneal line (in degrees) of 10 subjects.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Orthotist 1 Cast 1</th>
<th>Orthotist 1 Cast 2</th>
<th>Orthotist 2 Cast 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.5</td>
<td>0.5</td>
<td>1.0</td>
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<tr>
<td>2</td>
<td>0.5</td>
<td>1.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>-0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>0.5</td>
<td>-1.0</td>
</tr>
<tr>
<td>6</td>
<td>-1.0</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
<td>-1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>1.0</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

of the foot. The material must be stretched over the foot to get the precise contour whilst it is still transparent (in its elastic state). Applying pressure to the material when it is not transparent will distort the joint alignment and soft tissue of the foot; however, the user must also be careful to control the temperature of the material so that it will not cause discomfort to the patient. The water bath must be clear from impurities so that the water-heated material can be securely bonded together; however, difficulties may occur when detaching and removing the splint from the foot if the bonding area is too large or the user applies excessive bonding pressure.

Both of the testers who participated in the experiment were experienced orthotists who specialized in foot orthotics. The reliability test may well have been different if the testers had not been properly trained and did not have sufficient experience. There have been attempts to apply computer-aided-design and computer aided-manufacturing (CAD/CAM) systems in foot orthotics; however, the existing systems are mainly for the provision of accommodative orthoses for diabetic foot problems or posted functional foot orthoses which is being reviewed. The successful application of orthotic intervention to control foot alignment will still depend on systematically trained professionals offering the quality service using appropriate innovative technology.

Conclusion
Low temperature thermoplastic material with high elasticity and self-bonding properties has been used for the foot impression procedures. Results of this study showed that properly trained and experienced professionals can perform the manipulated foot impression procedures with good reliability. Subsequently orthotic intervention can be performed in a more consistent manner.

REFERENCES


